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Radar Communications

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Radar Analysis Branch
Radar Division

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Means of communicating through a radar without significantly altering its performance are described. A number of design alternatives such as radar type, antennas, transmitters, frequency diversity, message relays, channel allocations, and modems are considered, and recommended communication and radar-intermesh procedures are given. A demonstration radar-communication system under construction is outlined. In addition, ways of effectively using a radar-communication system are explored. Finally, a planned demonstration of the communication of surveillance-radar data between two sites on the Chesapeake Bay using radar communication is described.

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CONTENTS

INTRODUCTION 1

DESIGN OF A RADAR-COMMUNICATION SYSTEM 1

Design Alternatives 2

Candidate Radar Types 2
Sharing of Resources 2
Transmitter Types 4
Message Relays 5
Spread-Spectrum Techniques 5
Multipath Considerations 6
Multiplexing of Radar and Communication Signals 6
Channel Allocations 7
Modem and Coding Considerations 8

Tentative Design for Experiments 9

Sites and Major Equipment 9
System Timing 10
The Modem 11

APPLICATIONS OF A RADAR-COMMUNICATION SYSTEM 11

Overview of Applications 12

Ship Platforms 12
Airborne Platforms 12
Satellite Platforms 12

A Useful Demonstration 13

SUMMARY 14

REFERENCES 15

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RADAR COMMUNICATIONS

INTRODUCTION

Military electronic systems are usually designed to perform such functions as general surveillance, identification, fire control, communications, and jamming. All such functions involve the transmission and/or reception of signals by electromagnetic propagation. Although in general these functions require subsystems with considerable overlap (such as antennas, transmitters, receivers, signal processors, and data processors), most military electronic equipment is designed and constructed to perform only limited tasks, and the mission goals are usually met with a collection of separate systems. In some instances, however, two or more systems could be combined to obtain cost-effective performance by sharing expensive components or subsystems.

These are stories, perhaps not completely valid, about the sharing of system resources in the past. During World War II, identification interrogation messages were transmitted and replies were received on the radar. Later, IFF systems became completely separate from radar. There is considerable interest today in placing the challenge portion (not the air-traffic-control function) of the IFF system back into radars. The SAGE (Semiautomatic Ground Environment) system used long-range surveillance radars to communicate information. The electronic-support-measure (ESM) and radar systems have shared antennas in some surveillance systems and have shared a number of components in missile weapon systems. For example, a missile might home on either radar reflections or jamming signals. Radars have often acted as jammers, even if inadvertently, by providing strong interference to other electronic equipment. In some fire-control systems, commands or data are transferred to the missile with the radar.

We will explore in this report two major areas: design of a radar-communication system and applications of such a system. We will restrict the discussion of radar-communication design to the use of a scanning surveillance radar. We will look at a number of alternatives and discuss a tentative design to be implemented for demonstration. After we address possible applications of radar communications, we will give plans for a demonstration of an effective use of a radar-communication system.

DESIGN OF A RADAR-COMMUNICATION SYSTEM

We will use a conventional scanning surveillance radar as our baseline system and see how we can send messages over it without significantly altering radar performance. Since we are not allowing the radar function to significantly degrade, we will consider only systems with high-gain antennas and high-power transmitters (the bulk of the surveillance radar systems in use).

Manuscript submitted May 22, 1981.

Design Alternatives

Candidate Radar Types

Most radar systems can be classified as surveillance, fire-control, or phased-array radars. A phased-array radar to some degree can perform both surveillance and fire control simultaneously. When not in use, the fire-control radar could be used to transmit messages. The problem is that in a hostile environment the fire-control radar may not be available to point its beam in the direction required for communications when one might most need to send messages. Because of this problem with availability of beam pointing in a hostile environment, communication through the fire-control radar (other than communication used now in some fire-control solutions) is of little interest in this study. However, much of the discussion would apply to a fire-control-radar communication system when the availability of beam pointing was not a problem.

The beam of a surveillance radar covers a substantial volume of space in about 2 to 10 seconds. Communication between two points in space could be established for short intervals of time once per scan as the beam sweeps over the recipient. During these intervals the radar would share its resources with the communication system. A similar behavior could be obtained with a phased-array system because of its beam agility. The beam can rapidly be placed at different pointing angles, and fire-control, surveillance, and communication functions could be time-shared (multiplexed) through the system. Since potential applications of radar communications are closely related to the types of radars, we will delay further discussion on this topic until the second half of the report.

Sharing of Resources

A design that only slightly degrades the radar's action when its resources are shared with the communication function requires use of the radar's high-power transmitter or high-gain antenna or both. Before we discuss the tradeoffs, we eliminate those candidates which would involve transmission or reception through the sidelobes of the radar antennas. Although communications could sometimes be established using the sidelobes, it would be erratic because of the nulls and not available at times. Moreover, the trend is toward the use of low-sidelobe antennas.

Table 1 indicates different ways we can share radar and communication resources. A radar antenna using only the main beam is considered for use in both message transmission and reception. The addition of a low-gain auxiliary antenna of the type commonly used in communication systems is also considered for both message transmission and reception. The transmitter also can either be the radar's or be an auxiliary transmitter used only for communication. There are eight ways to select a transmitter and transmitting antenna at the message transmission site and an antenna at the receiving site: the seven ways of sharing listed in Table 1 and a completely separate communication system. There would have been more combinations in Table 1 if transmission and reception through the radar antenna sidelobes had been included as a separate category.

First let us consider combination 1 in Table 1: communication using the radar transmitter and antenna for transmitting and using a radar antenna at the receiving site. This system would have enormous signal-to-noise ratios at conventional ranges because of the high transmitter power and high antenna gains prevalent in most radars. The difficulty with this system is the requirement that the beams formed by the radar antenna be pointed at each other. For systems which rely on the mechanical movement of the antenna for beam pointing, the use of the antenna for other purposes would have to be foregone during the communication time because of beam-pointing requirements and antenna inertia. Because of this substantial penalty, systems involving the use of mechanically steered antennas at both transmitter and receiver will not be considered further.

Table 1 — Possible ways a communication system can share radar resources at either or both the transmission site and the reception site. Use of a radar resource is indicated by R, and use of an auxiliary low-power communication-system resource rather than a radar resource is indicated by A.

Combination	Transmitter and Antenna to be Used for Message Transmission		Antenna to be Used for Message Reception
	Transmitter	Antenna	
1	R	R	R
2	R	R	A
3	A	R	R
4	A	R	A
5	R	A	R
6	R	A	A
7	A	A	R

For phased-array systems with agile beams, communications using both transmit and receive radar antennas could be time-multiplexed with other radar functions without conflict. The difficulty in using phased-array antennas is the acquisition of synchronization so both beams can be simultaneously pointed at each other. Just as in the case of mechanical beam motion, this sytem can provide tremendous signal-to-noise ratios when required in line-of-sight communication. Furthermore, in many cases a tropospheric-scattering communication link could be set up between stations that are not in line of sight of each other. Although large losses are present in the tropospheric-scattering link, the two radars could probably provide sufficient signal-to-noise ratio. There is also the possibility of using bistatic scattering from airborne targets to couple the electromagnetic energy over the horizon. However, since there are so few phased-array radar systems in use, this option will not be examined further.

Combination 2 in Table 1 uses the radar antenna and transmitter to send the message and uses an auxiliary low-gain antenna for reception. This system also has extremely high signal-to-noise ratios at ordinary ranges because of the very high effective radiated power. In fact the system is virtually jamproof unless a jammer expends enormous resources very near the receiving site. With a surveillance radar, messages can be transmitted to a given site as the scanning beam passes over it. Only a minor modification to the radar is required such that the radar waveform is altered for communicating data when the beam scans over the given site. It is this configuration which is of the most interest in the remainder of the study. Higher rates of communication data could be obtained if necessary by simply giving up the radar at times and pointing the radar antenna toward the receiving site. Although both modes should be explored, the most useful mode is thought to be message transmission as the beam scans over the receiving site.

Combinations 3 and 4 in Table 1 are the same as combinations 1 and 2 except that an auxiliary transmitter is diplexed with the radar transmitter. Some slight advantage is gained because radar and communication can exist simultaneously for a short time during the radar pulse. As we will see, this improvement can easily be overcome by dropping a radar pulse or so and transmitting for longer time intervals for a pulse-repetition interval or two. All that is required is that the

average power capability of the radar transmitter be improved some. A substantial disadvantage is that two transmitter chains need to be provided and multiplexed together through the radar antenna. For this reason we will not consider combinations 3 and 4 further.

Combinations 5 and 6 in Table 1 involve the switching of the radar transmitter to a low-gain antenna during communication and back to the high-gain radar antenna for the radar function. This mode has the attraction that most radars require long dead times for listening, during which times the high-power transmitter could be used for communication. Of course, the transmitter would have to be properly designed to handle the extra average power load. Furthermore, a high-power microwave switch would be required, and such a switch is not simple to make with use of currently available microwave components. The improvement in effective radiated power of this configuration over ordinary communications is only that by which the radar transmitter power would exceed nominal communication-transmitter power. Although combinations 5 and 6 are interesting because one transmitter does the work of two, we will not pursue them further in this report.

Combination 7 in Table 1 is identical to a separate communication system except that the messages are received by the high-gain radar antenna. This would improve the signal-to-noise ratio, especially in jamming. The problem is to communicate when the receive antenna beam is pointed toward the transmitter. The required synchronization could be achieved by a protocol system involving transmissions at both sites.

In addition to the combinations in Table 1 for sharing antennas and transmitters, the communication system and the radar system could share a receiver. This option is not interesting, because we probably want to operate the two systems at different frequencies to avoid interference and do not normally want to time-share. Besides, superheterodyne receivers (which would normally be used) are not large or expensive, and it would probably be best to use one for each job.

Other resources such as waveform-generating circuits are sometimes similar in radar and communication systems. For example, phase-shift-keyed modulation used in communications is similar to a binary-phase pulse-compression code as used in radar. These devices are usually special purpose and are not large; consequently no attempt is made to exploit any potential for common usage.

Briefly summarizing our discussion up to now, we find the preferable radar communication system shares the radar antenna and transmitter. All other functions are performed separately. Depending on the configuration chosen and the type of radar used, significantly different capabilities and sets of advantages and disadvantages can be produced. Before we become more specific, however, we want to discuss in general some factors which enter into the design. We next look at the radar transmitter.

Transmitter Types

Since we are to use the radar transmitter for both radar and communications, its design is critical in the operation of the system. The transmitters we will discuss are those based on the gridded tube, the transistor amplifier, the klystron, the traveling-wave tube (or TWT), the crossfield amplifier, and the magnetron.

The gridded tube at the lower microwave frequencies exhibits good performance with regard to bandwidth, gain, efficiency, peak power, average power, etc. In the past it was used frequently at UHF. For example, two predominant Navy radars, the SPS-40 and the APS-125, use gridded-tube amplifiers.

By parallel arrangements of a large number of transistors, high-power sources can be made at the lower microwave frequencies. With the newer gallium arsenide devices, the frequency range can

be extended up through X band. These amplifiers exhibit good bandwidth, high average and peak power, and graceful degradation on failure.

Both the gridded tubes and transistor amplifiers, where applicable, are good candidates for radar communication. First, they have sufficient bandwidth so that interference between radar and communication functions can be avoided by frequency separation even if wide-bandwidth signals are used. Second, they can be designed to yield sufficient average power for both radar operation and communication operation.

In contrast to the intensity-modulated devices just described, we next consider some velocity-modulated devices. The two common ones are the klystrons and the TWTs, which differ only in their slow-wave structures. These amplifiers, except for probably the narrow-bandwidth klystrons, can also make good choices for radar communications. They, too, can be designed to provide enough average power for both functions and have enough bandwidth for good frequency separation.

Finally, we look at the crossfield amplifier and the magnetron, which is also a crossfield device. The crossfield amplifier has low gain and is usually used as an output stage on a fairly high-power transmitter. It is also limited in its average-power-handling capability. Probably the best way to use the crossfield amplifier is to leave it turned off during communication, in which case it acts as a waveguide, and to turn it on for the radar. The good average-power capability of the driver stage could then be used for both communications and radar.

The magnetron is by far the most widely used microwave source for radar. It is small, is rugged, has high efficiency, and is capable of high peak power. From the point of view of radar communications, it has some serious limitations. It is an oscillator, which limits the choice of modulation types. It is possible to generate on-off keying and differential phase modulation directly at high power. The tube is limited in average power; consequently it does not have the energy to share with the communication system that some of the other sources have. The tube is hard to tune in frequency, because it is tuned mechanically at high power. This further restricts its use. Even though this device is not as amenable to radar communications as others, it may be an important one simply because of cost and weight. However, in this study we will be primarily concerned with amplifiers having fairly wide bandwidths and good capabilities for handling peak power and average power.

Message Relays

Since only line-of-sight propagation is possible with radars (except for anomalous propagation modes), a question arises as to how messages can be transmitted to a recipient over the horizon. The only way of achieving this under normal propagation conditions is by relaying the messages. There are two principal ways of relaying messages. The first is by use of an RF relay, which basically receives and retransmits at an offset frequency. This procedure is not practical in the system we have envisioned, because the relay radar would in general not have its transmit antenna pointed in the proper direction when a message requiring relay arrived. The other procedure, using concepts borrowed from packet networks [1], is to simply send addressed messages (packets) between users. A participant can schedule and retransmit a packet it received on its own communication system, thus providing a relay capability. The packet-network concept seems to be the concept best suited for radar communications.

Spread-Spectrum Techniques

A means of obtaining antijam capability in communication systems is to use spread-spectrum techniques. These techniques work by spreading the jamming power over a wide bandwidth relative to the (despread) signal bandwidth. This in effect decreases the jamming power density, which

becomes closer to the thermal noise level. However, the signal energy remains the same, and we in effect have an improvement in signal-to-jam ratio by the ratio of the signal's spread bandwidth to its unspread bandwidth.

There are two basic types of spread-spectrum techniques: pseudo-noise spreading and frequency hopping. Pseudo-noise-spread signals are usually generated by phase-modulating the transmitted signal at a rate much faster than the bit rate. The receiver applies the complementary phase-modulating sequence to effectively remove the phase modulation. Synchronization must be acquired such that the phase shifting at the receiver is in exact step with the received spread-spectrum waveform. In frequency-hopping systems, the frequency is usually changed every symbol (which may be one or more bits). The receiver again must be synchronized so its local oscillator will be in step with the incoming waveform. Of course both pseudo-noise spreading and frequency-hopping techniques can be applied to the same system.

Spread-spectrum techniques are a way of combatting jamming and unintentional interference. We will not seriously consider the techniques further as antijam measures in this study for the following reasons. First, if we use the high-power transmitter and high-gain antenna of the radar, we significantly improve the antijam capability over more conventional communication systems, and more jamming margin is probably not required. If a number of our own emitters are tuned to different frequencies across the band, we can force a jammer to spread his power without ever using the more expensive spread-spectrum techniques.

Multipath Considerations

Signal fading, often caused by multipath, can be combatted using frequency or space diversity. One way of operating in multipath is to transmit the same message on several frequencies and choose the frequency which fades the least. Another is to shift frequency every bit and use error-correcting codes to fill in those bits which have faded out. Multiple antennas could be used, with the system selecting the antenna with the strongest signal. A third way of operating in multipath is to use a protocol requiring retransmission upon error detection.

Our initial design concept has no special provision to combat signal fading. We hope to use the large effective radiated power of the radar to give enough fade margin for adequate operation. Good results are anticipated with the possible exception of occasional very deep fades in jamming. This anticipation of good results needs to be confirmed experimentally.

Multiplexing of Radar and Communication Signals

There are three basic approaches to the multiplexing problem: let the message waveform serve as the radar waveform, combine two signals at different frequencies, and communicate and provide radar at different times. The first option, letting the radar and message waveform be the same, has some strong disadvantages. For example, let the message consist of 128 binary phase-modulated bits. The reflected radar signal could be matched-filtered using a device dynamically programmed with the message bits. Unfortunately, high range-time sidelobes would often occur, because there are only a few codes with good range-time sidelobe properties. What we might do is encode our messages into only those codes which have good range-time sidelobe properties. However, the available data rate would be lowered tremendously. It appears, therefore, that only a limited data rate with respect to the signaling bandwidth can be transmitted if low range-time sidelobes are to be maintained for the radar.

There is an alternative. Consider allowing large range-time sidelobes, so messages can be efficiently transmitted. The reflected waveform is matched-filtered to the transmitted message, so that optimum detection is possible. However, because of the large potential range-time sidelobes, the

range resolution of the detections is no better than the transmitted message length. For example, a 1-μs pulse phase-modulated at a 100-Mbit/s rate would provide 100 bits of data, and if the reflected waveform is match-filtered, good radar detection performance would be obtained. However, the range resolution would be no better than that range corresponding to a two-way propagation time of 1 μs.

The second basic approach to the multiplexing problem is to diplex two transmitters at different frequencies, allowing both communication and radar action to take place simultaneously at the expense of an additional transmitter. This option is simple and should not be overlooked. The communication transmitter can have much less power than the radar transmitter and yet excellent communication can be obtained.

The other basic approach is to provide communication and radar at different times through the same transmitter and antenna chain. This approach is probably the option of most interest. Time can be alloted between communication and radar in various ways. One possibility is to split the radar pulse, using the first part for communication and the last part for radar. Other possibilities are to replace some of the radar pulses with communication pulses or to use one scan for radar and another scan for communication. If the transmitter has good average-power capability, the communication pulse may be configured to last a lot longer than the radar pulse, and a much larger amount of information may be transferred.

In summary it appears difficult, except in special applications, to use the same waveform for both radar and communication. In most instances it seems appropriate to simply time-multiplex the radar and communication waveforms.

Channel Allocations

One requirement in a multiple-user communication system is that the users not interfere with each other. We will examine several ways of meeting this requirement.

One way of keeping users from interfering with each other is to have each transmit only at preassigned times. This is called time-division multiple access (TDMA). A similar but more flexible system is sometimes referred to as dynamic reservation. This is a TDMA system in which the transmission time allocations of the participants are changed as their needs change. A small amount of overhead time is required for management of time-slot allocations.

An example of a random-access system uses the so-called ALOHA channel, which is named after an early experiment at the University of Hawaii [2]. In this type of system a user sends his message whenever he has one. As long as the total number of messages sent by all users is small, the chances of message collisions are small. Reception of each message is confirmed with a return acknowledgment. If an acknowledgment is not received, the message is retransmitted at a new random start time.

Another example of a multiple-access system is a polling system. One unit polls the others in sequence. The unit being polled can transmit while the others remain silent.

Another means of preventing interference between participants is to assign each participant a different frequency. This is spectrally inefficient unless the participants have constant data rate and 100% duty cycle.

The last way of keeping users from interfering with each other that we will consider is spatial filtering. High-gain antennas can be pointed on transmission and/or reception so that only selected

participants are affected by message transmission. A number of participants can transmit at the same time to different spatially separated users without interfering.

For radar-communication systems it appears that some form of slightly structured random access might be most appropriate for the following reasons. First, if the high-gain radar antenna is used for transmission, a user will hear messages only from those participants whose beams are pointed toward him. For any one user this occurs only a small fraction of the time. The chance that two beams are pointed toward a particular user at the same time is slim. Furthermore, the chance of a message collision can be further reduced by restricting the messages to short bursts. The chance of a user simultaneously receiving messages from two participants is slim even if both their beams are on the user. Even though message collisions are infrequent, they can occur, and some strategy is required to prevent loss of data.

Applications are conceivable in which the loss of a message would not significantly impact the system, and the few messages which were lost by collision could simply be forgotten. In other applications an ALOHA-type protocol could be adopted which requires all messages to be acknowledged, either via a return message when the high-gain antenna reaches the correct position or by use of a separate transmitter and antenna for sending the low-data-rate acknowledgment immediately on message receipt. The original sender can then decide whether to retransmit.

A source of interference that does not occur in normal communication is the disruption of a message being received caused by one's own radar pulse. Even if the receiving antenna and the radar antenna are different and the communication and radar signals are at different frequencies in the band, good isolation may still be difficult to achieve. If sufficient isolation cannot be achieved, the communication system will have to be blanked during the radar pulse. A protocol system can be used to adjust the times of the radar pulse transmissions so that outgoing radar pulses do not collide with incoming message bursts. One such protocol system will be discussed later as it relates to the experiment.

Modem and Coding Considerations

The design principle applicable to modulation and coding for radar-communication systems do not differ significantly from those applicable to ordinary communication systems. Consequently, only an outline of the required functions will be given here. For simplicity, only binary communication will be considered. The coding functions include the encoding of data or messages into binary bits, the removal of redundancy in the data, the application of error correction or detection codes, the application of protocol or control data, and the encryption of the data stream.

The modem transmitter converts the resulting bit stream into a waveform which is suitable for transmission at microwave frequencies. The receiver may have to adjust its local oscillator so that the signal falls in the modem receiver passband. The conversion of the received waveform by the modem receiver back into a bit stream is more complex. First, energy must be detected. If coherent detection is required in the modem, the receiver must be phase-locked to the carrier frequency of the transmitted waveform. The sampler timing must be adjusted so that samples are taken at the optimum points within the received bits. To allow the modem's receiver enough time for these adjustments, the modem's transmitter is generally required to transmit a predetermined preamble or synchronization waveform immediately before the actual information-bearing portion of the signal.

Finally, the inverses of the coding operations can be performed on the output of the modem's receiver. It is beyond the scope of this report to discuss these standard communication functions in detail.

Tentative Design for Experiments

In the discussion so far, we have described in a general way the design alternatives and considerations in a radar-communication system. We will next concentrate on a particular radar-communication system which we will construct and test.

We have chosen the Senrad radar, which operates at the Chesapeake Bay Detachment of the Naval Research Laboratory (NRL). The Senrad radar is a 2D fan-beam L-band radar. The antenna mechanically rotates in azimuth with rates between 7.5 and 15 rpm. The Senrad radar is similar to the SPS-49 being introduced into the fleet.

The communication messages will be transmitted through the Senrad transmitter and its high-gain antenna. The receiving site will use a nearly omnidirectional low-gain antenna and a conventional receiver. A system of this type would be virtually unjammable in most environments, because a jammer could not approach Senrad's transmitter power and antenna size from a location as near the receiver. This system could be used in land-based or sea-based long-range surveillance systems. Of course other configurations could benefit as well from the experience gained with this system.

Sites and Major Equipment

We have chosen two sites on the Chesapeake Bay for the experiments. The Senrad radar is at the Chesapeake Bay Detachment (CBD) of NRL on the west side of the bay. The other site is the Tilghman Island facility of NRL about 9 nmi almost due east of CBD on the east side of the bay. An SPS-12 radar is on Tilghman Island. Block diagrams showing the major components of the radar communication system at each site are given in Fig. 1.

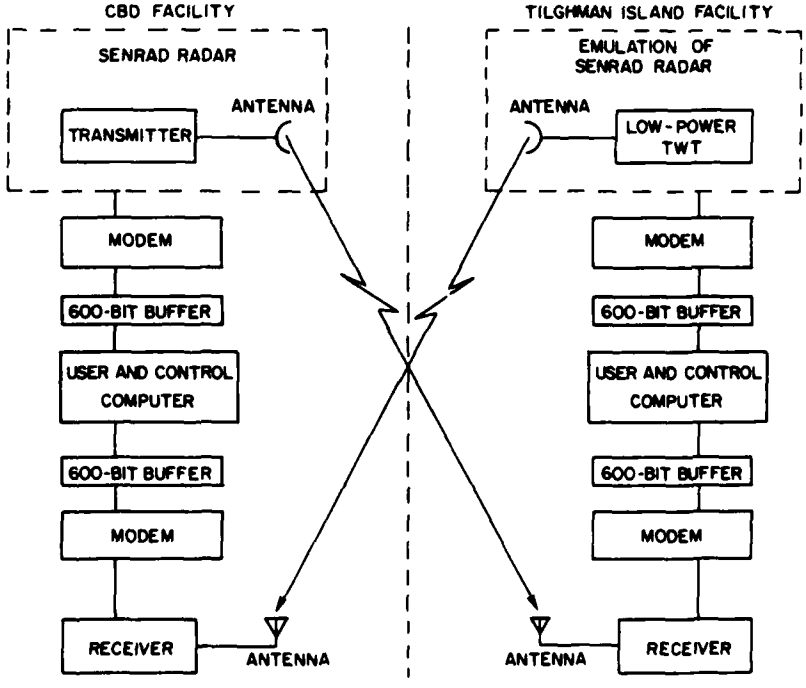

Fig. 1 — Experimental radar-communication system

The communication equipment at *each* facility will be identical except that the Senrad communication will be emulated at the Tilghman Island facility. This is necessary, since only one Senrad radar exists. Because the distance is small, the emulator can use a low-power transmitter. Furthermore, it can use a nonrotating low-gain antenna and simulate Senrad's main-beam scanning by transmitting only at those times when the beam of the rotating antenna would have passed over the CBD facility. This configuration will allow us to fully test both the transmission and reception portions of the radar-communication system by employing the Senrad radar at the CBD facility.

Communication will take place as follows. A message is first formed in the control computer and placed in a 600-bit buffer. The message is assumed to already include both protocol information and any necessary coding operations. At the appropriate time as determined by the timing circuits, the message in the buffer is converted to a waveform by the modem and transmitted through the Senrad radar's transmitter and antenna. The message is received through a low-gain antenna (small horn or dipole) and a conventional receiver. The receiving modem converts the incoming waveform to digital data, which are stored in a 600-bit buffer until they can be read into the control computer. The control computers will probably be Data General NOVA 800s, because they are readily available.

System Timing

The radar and communication signals will be time-multiplexed as follows. Senrad normally transmits a pulse train consisting of short-range pulses followed by a long-range pulse. This waveform is then repeated several times as the radar antenna rotates in azimuth. If a message is awaiting transmission when the radar's beam begins to cross over the other site, the radar's long-range pulse will be replaced with a 120-μs communication burst. We must therefore give up the radar's long-range pulses over a beamwidth in azimuth whenever we communicate. The short-range radar action will remain unmodified. Of course we could use only every other long-range pulse for communication. This would halve the bit rate but still allow some long-range radar action. The number of long-range pulses which are present while the beam is sweeping over the Tilghman Island facility is about six. If all six would be appropriated for communication use, the data rate for the given 600 bits per communication burst would be 3600 bits per scan. With a radar scan period of 4 seconds, the data rate per receiving site would be 900 bits per second.

The required interfaces between the existing radar and the communication portion of the system are minimal. The timing of the communication functions can be determined from the radar azimuth and several control signals which presently exist internal to Senrad. The communication system will send back to the radar the modulated communication waveform and a signal controlling the RF switch which determines which waveform, communication or radar, is to be sent to the transmitter. The control signals required from Senrad include the pulse train used to gate the Senrad pulse-expansion lines and thus establish the times of RF transmission, three binary signals indicating which type of pulse Senrad is to emit, and a receiver-blanking signal to protect the receiver during RF transmission. A simple logic circuit using these control signals will be used to control the communication system's transmissions.

To prevent loss of received messages during the Senrad radar's transmissions (while the communication receiver is blanked), a protocol can be adopted which will allow Senrad to know in advance the time of an incoming message and change the timing of the radar pulses appropriately. The message sender could make the intended recipient aware of the time at which data would be transmitted as follows. At a predetermined time before the message burst, the sender transmits three short warning bursts. For simplicity, these warning bursts can be made to look exactly like message bursts, but without the message, that is, they need to contain only the preamble used to synchronize the receive modem, and possibly a sender identification. The intervals between the

warning bursts can be chosen so that it will be impossible for the receiver to be blanked during more than one of them. If these intervals are also made unequal, then by measuring the times of arrival of only two of them it will be possible to know the timing of the message burst to follow. Suppose for example that it was known that the first two bursts were always separated by 200 μs, the last two were always separated by 400 μs, and the message burst followed the last warning burst by 400 μs. Blanking the receiver during the first warning burst would result in an interburst-interval measurement of 400 μs. If it was the second pulse blanked, the measured interval would be 600 μs, and if it was the third the measurement would be 200 μs. Since each case would result in a unique measurement, the identity and time of the missing burst and hence the expected time of the message burst could be uniquely determined. Senrad radar pulses can then be delayed if necessary to prevent blanking the message burst. This warning protocol and the ability on the part of Senrad to alter the timing of pulses will not be part of the initial experiment but will be added at a later date.

The Modem

The modem will convert the data to a waveform suitable for microwave transmission and return the waveform to data at the receiver. Although many different modulation procedures could be used, we chose high-modulation-index frequency-shift keying (FSK) because of its simplicity, its nearly-constant-envelope signal, its tolerance of degraded channel frequency response, and its ability to survive Class-C amplification in Senrad. The penalty we must pay for these features with respect to some other modulation techniques is that more RF bandwidth will be required to send data at the same rate.

The data stream can be modulated into a waveform by switching between two oscillators according to the binary data sequence. The waveform is demodulated by passing the signal through narrowband filters centered on the two oscillator frequencies. The two filter outputs will be envelope-detected and compared to see which is the largest. The output of the comparator will then be sampled at regular intervals to yield a binary sequence which matches the transmitted binary sequence. Simulation has shown that if a 5-Mbit/s data rate is used, a tone spacing of 12 MHz and filter bandwidths of 12 MHz centered on the tone frequencies are adequate design parameters. These figures allow for reasonable tolerances in the components. The overall bandwidth required then is 24 MHz.

The modem must also synchronize bit timing, detect the start of a message on the received waveform, and possibly perform automatic gain control (AGC). Since the design has not been fixed at the time of this writing, our comments will be brief. A preamble will probably be attached to the transmitted waveform. The preamble will probably consist of an alternating sequence of ones and zeros followed by a code indicating the beginning of a message. The alternating sequence will allow time for the AGC to settle and can be used to initially adjust the sampling times so that samples are taken at the optimum times during the bit intervals. The code in conjunction with an energy detector will indicate the beginning of a valid message.

APPLICATIONS OF A RADAR-COMMUNICATION SYSTEM

Up to this point we have described radar-communication design alternatives and a specific design using the Senrad radar for demonstration. We next consider ways in which a radar-communication system could be used and, finally, describe tentative plans for real-time demonstration of a useful configuration.

Overview of Applications

In discussing the possible uses of radar communication, we will consider ship, airborne, and satellite platforms separately. We will not discuss any of the applications in depth. We first consider ship platforms.

Ship Platforms

Several ships within line of sight of each other could communicate using their radar with degradation in radar performance. This communication between ships could help coordinate resources and be used to construct an improved surveillance picture. This assumes operation as a stand-alone system. If wide-area command-and-control links were available such as Link-11 or JTIDS, the radar-communication system could be used to pass to nearby ships the information or data designated for local distribution only. This additional communication capability could lighten the load on the other communication systems by not cluttering them with information that will benefit only a few users.

The radar-communication system on a ship could also be used to communicate with airborne platforms. For example, it could be used to vector aircraft or control missiles.

Because of the enormous effective radiated power of the radar-communication system, it could provide a last-ditch communication system that could operate when others have been jammed by hostile forces. In this environment a wide variety of data or information could be transmitted.

If voice communication became a top priority, the surveillance-radar antennas could be stopped and voice transmitted using small buffered delays. Otherwise, the voice data could be stored during the radar scan for transmission at a high rate in pulse bursts as the radar beam passed over the other ship. The only noticeable effect of such storage would be a time delay of 4 to 6 seconds in each communication path.

Airborne Platforms

We next consider the airborne platforms. Possible applications of radar communication from aircraft are essentially the same as we described for ships. They include local stand-alone capability, aid to wide-area command-and-control communication systems, missile and platform control, last-ditch communication, and voice.

The radar communication from ships, surveillance aircraft, and fighter aircraft would probably all be at different frequencies. For example, the ship's radar-communication system would operate at L band, the surveillance-aircraft's system would operate at UHF, and the fighter-aircraft's system would operate at X band. If the ship had receivers at L band, UHF, and X band, it could receive high-power radar-communication messages from all three types of platforms. If the surveillance aircraft and fighter aircraft had L-band receivers, radar communication could be set up from the ships to those aircraft. The ship's L-band radars could then transfer messages to the aircraft at L band, and the aircraft radars at either UHF or X band could transfer messages to the ships. Messages between aircraft could be relayed through ships or transferred directly by providing receivers on the aircraft in the appropriate frequency ranges.

Satellite Platforms

Finally we consider satellite platforms. We assume that the satellite's role is to gather intelligence. If the satellite has a radar, its large effective radiated power could be used to send information

to earth in spite of jamming. We could conceivably interrogate and control the satellite radar with a high-powered radar on earth using radar communication. The satellite radar and the earth-located radar would probably operate at different frequencies.

A Useful Demonstration

We will now describe our tentative plans for a useful demonstration. The demonstration is divided into at least two phases. Phase one, to be described first, will be fairly limited in scope, with most of the equipment being currently available. A block diagram of the major equipment items and their relationships is shown in Fig. 2. The equipment we have available includes the Senrad radar, the SPS-12 radar at Tilghman Island, the SPS-39 radar at CBD, detectors for both the SPS-39 and SPS-12 radars, three NOVA 800 minicomputers, and two versatile digital-data recorders capable of recording detection, track, or video radar data. The detector for the Senrad radar will probably be built as part of another project. A computerized display will probably be borrowed for the CBD facility, and the Tilghman Island facility will probably not have any display other than a PPI. A disk-operating system and various peripherals support the NOVA 800 computers. The software for the automatic tracking systems already exists.

The planned demonstration for phase one is as follows. Each site will maintain target tracks in their own computers (1 and 3) using data from the local radar. Periodically (every scan time of the Senrad radars) each site will transfer its track file to the other site using the radar-communication facility. If too many tracks are present, a subset will be selected for transmission. This will demonstrate the two-way transfer of data. Only at the CBD site will there be a demonstration of how the transferred data will be used. NOVA 800 computer 2 will accept the CBD and Tilghman Island track files and construct a more complete air picture using data from both sites.

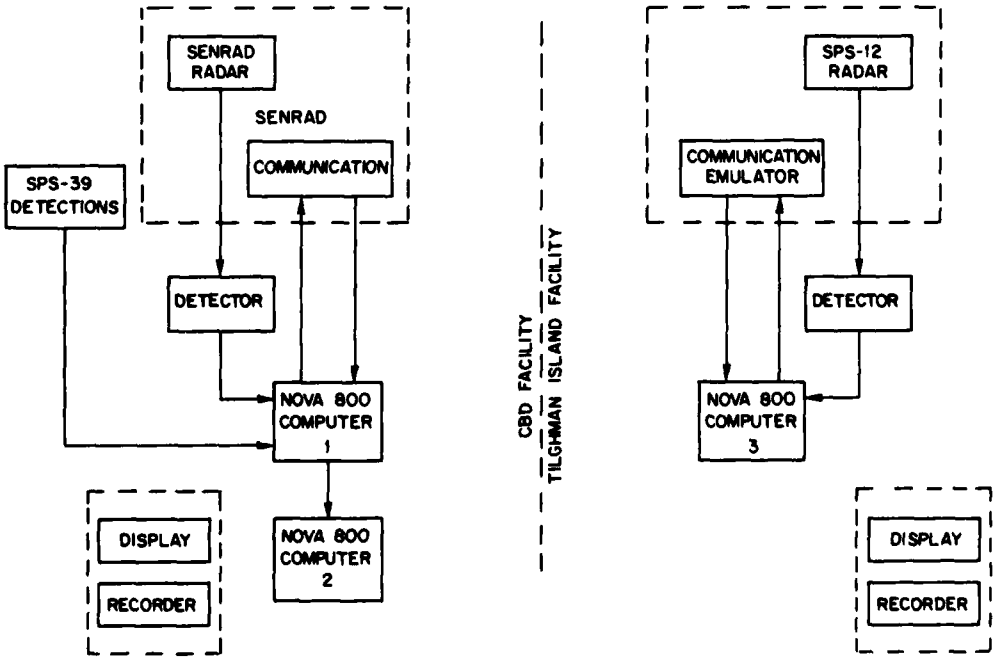

Fig. 2 — Equipment components for phase one of a useful demonstration of radar communication

In phase one the only interaction envisioned between the sites is the periodic transfer of the track files. The other major part of phase one is the collection of data to be used in nonreal-time studies. Work which needs to be performed in phase one includes the design and construction of computer interfaces, the modification of the automatic tracking software residing in computers 1 and 3, and the development of software for combining the data from the two sites in computer 2.

Phase two of the demonstration cannot be achieved within the problem's current time and fiscal constraints. In this second phase we would probably construct a highly interactive system which would improve coordination, provide efficient use of the radar-communication channel, and possibly improve the air picture. The basic architecture would probably, at least to some extent, follow the structure described in Ref. 3. However, because we are not near to proposing this phase, any description now would be quite speculative. The lessons learned in phase one will probably be instrumental in setting up a more elaborate demonstration.

SUMMARY

In this report we described the current status of the radar-communication system under study and related many of the things considered in reaching the current status. We began by describing why it may be advantageous in some cases to share several functions in one piece of equipment. Specifically, we looked at communicating through the radar.

Although a number of options were considered, in most cases the best way of providing both radar and communication would be for them to share only the radar's antenna and transmitter. The communication receiver would be rather conventional and probably use an omnidirectional antenna. For large data rates, any of those transmitter types which have high average power and wide bandwidth would be acceptable. Message relays are probably best provided using packet network concepts.

Although spread-spectrum techniques are currently popular, we view them as unnecessary for radar communication, because we would already have good antijam margin due to the extremely high effective radiated power. Multipath fading is a valid concern in these systems. For now we hope the large effective radiated power will be sufficient in most fading conditions.

We decided to time-multiplex the radar and communication waveforms. Because of the narrow transmit antenna beams and the short bursts of data in time, collisions of messages from different transmitters at one receiver are unlikely. Therefore, a lightly structured random-access system with protocols was thought to be adequate to avoid most message collisions. The modem and coding functions are standard and were briefly reviewed.

A demonstration radar-communication system under construction was outlined. The Senrad radar at NRL's Chesapeake Bay Detachment and a Senrad emulator across the bay on Tilghman Island are to be used. Some of the radar pulses will be replaced with communication data bursts when the radar's beam sweeps over the receiving site. We hope to transfer 600 bits per burst and use about six bursts on each pass of the antenna beam over the receiving site.

We next consider possible applications of radar communication. They include local stand-alone data exchange, aid to wide-area command and communication, missile and aircraft control, last-ditch communication, and voice. We briefly described how radar communication between ships, surveillance aircraft, fighter aircraft, and satellites could take place even though some of the radars would be at different frequencies. Finally, we described our plans to demonstrate, using radar data at the CBD and Tilghman Island sites, how radar communications could be used to construct a better air picture. A much more elaborate demonstration not in our current plans was mentioned.

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